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Design Procedures for Soil-Lime Stabilization for Road and Railway Embankments. Part 1 - Review of Design Methods

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Abstract

When selecting the appropriate materials for constructing road infrastructures, an important way for minimizing both the economical and environmental impact is to make use of lime for treating soils that are not suitable for road or railways construction.
Advances in lime stabilization technique allowed the successful use of this technique also for improving the bearing capacity of the subgrade, with noticeable savings on both aggregate and disposal charges.
In this paper a review of internationally adopted design methods for soil-lime mixture is presented, in order to compare testing methods and requirements of the adopted criteria, as discussed in Part 2.

Keywords: soil stabilization; lime; mechanical performances; reuse of clay soils.

1. Introduction

(Lime treatment of natural soils is an advanced technology which has already been used for several years , successfully used for improving soil strength and stiffness properties, that allows to reuse fine soils as obtained from earthworks via immediate reduction in their plasticity index, improvement in their compaction properties and in their bearing capacity. In the long term, lime treated soils prove to have improved compressive strength and CBR [1], as well as increased resistance to frost.

Due to the volumes of material involved in construction of road, railways and airports, this kind of choice has a deep impact from the environmental point of view on the surroundings, especially as far as the preservation of the quality natural resources, such as mineral aggregates, as well as with regard to the need to limiting the transport of

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materials to construction sites and that of waste material to the dump (such as fine soils that are unsuitable, without any treatment, to be used for construction purposes). In this framework, a correct planning of earthworks that allows one to govern the need for supply material for embankment fill and for capping layer becomes one of the main aims of the project management, also in light of the increased awareness of environmental issues [2].

It is important to notice that, nowadays, soil stabilization with lime (or lime and cement) allows not only to use fine soils as part of the subgrade with high functional and mechanical quality [3], but also to consider them as structural part of the road pavement, even in the case of highly trafficked roads [4]. In fact, the long-term increase in structural properties of the subgrade in lime-stabilized soil allows one to consider it when in the pavement design phase, thanks to its contribution to the overall strength of the structure [5] [6]. It is crucial, in this technique, to perfectly control those elements that are, both in the phases of design and construction, able to guarantee the final quality and performances of the mixtures, in relation to their intended use.

After a general overview of the lime treatment technique, this paper details the most common International Technical Specifications for design of lime-soil mixtures, with a focus on the Italian ones, since they prove to be quite different from the others internationally adopted – in particular that described in the harmonized European Standard EN 14227-11 [7]. In Part 2, the Authors will present the comparison made between these methodologies, carried out via a wide experimental program, in order to verify the adequacy of the Specifications as well as of the requirements considered in the different design methodologies.

Nomenclature

PI	Plasticity Index
IBI	Immediate Bearing Index , in %
CBR	California Bearing Ratio, in %
Gv	Volumetric Swelling, in %
UCS	Unconfined Compressive Strength, in kPa
OMC	Optimum Moisture Content, in %
MDD	Maximum Dry Density, in kN/m^3

2. Effect of the lime on clay soils

The main factors able to affect this kind of treatment are those related to the identification parameters of the mixture constituents: soil, lime and, if necessary, hydraulic binder. The most significant parameters, for these specific purposes, are:

- soils: gradation (particle size distribution), plasticity, content of potentially disruptive substances, natural water content (which is fundamental for choosing the kind of lime to be used and its dosage), in situ density, presence of large elements that during the construction phase may hinder the mixing process or make it unacceptable from the economical point of view;
- lime (air lime): the form of the lime to be added to the mixture: ground quicklime (calcium oxide), hydrated lime (calcium hydroxide) – dry or in slurry form – and milk-of-lime suspension). Again, its content of free lime, its grading and, when using quicklime, its water reactivity. It is worth mentioning that, in the same construction sites, all three kind of lime may be used, depending on the need to achieve more or less noticeable variations on the water content of the soil to be treated during the construction phase;
- hydraulic binder: mutual proportions and nature of the constituents that are able to affect the kinetics of the hydraulic setting, performance level and compatibility with the chemical constituents of the soil.

As far as the mechanisms that rule the interaction between soil and added lime, these are generally divided into:

- immediate effects: these are obtained at the very moment of the addition (and mixing) of the lime to the soil;
- long-term effects: these take place with time (several months or also several years), after the laying of the mixture.

The followings may be ascribed amongst the so-called immediate effects: variation of the water content and modification of the geotechnical characteristics of the fine fraction, as due to the flocculation of the clayey fraction of the soil (mainly modification of the compaction characteristics of the soil and increase in the shear strength of the soil).

The long-term effects are due to the pozzolanic reaction of the air lime that, interacting with the chemical constituents of the clay, gives rise to mineral species of the same nature as those produced by the hydraulic binders. The addition of lime to the soil, in a strongly basic environment (pH $\geq$12), progressively dissolves the silica, aluminium and iron oxides (SiO_2, Al_2O_3, Fe_2O_3) that form the clay and, in the presence of water, it produces a reaction with them, giving rise to calcium silicate and aluminate hydrates (known as C-S-H and C-A-H, respectively).

This action takes places in three subsequent phases [8], with kinetics that is different from that of cement stabilization (single phase process) and in much longer times that depends on the clay mineralogy and structure. The third and last phase, which is also the one that brings to the greatest development of the mechanical resistance of the mixture, is evident just after several months of curing at ambient temperature.

Thus, when we want to use lime (or lime and cement) stabilized soils in capping layers and, therefore, it is important to reach some predefined threshold of mechanical performances for gaining the necessary resistance to water (or also to freeze-thaw) induced damage, the curing time of the mixture to be tested cannot be defined a priori (as in the case of the cementitious mixtures) but should be considered as a project variable to be taken into account during work planning. In other words, in relation to weather trends, during the design study of lime-soil mixtures, it would be necessary to study the development of the stabilization process with time, in order to evaluate the right times that allow one to reach the required mechanical performances and the needed stability in relation to the weather conditions (water soaking and freeze, particularly) [9].

3. Design criteria and quality control

A laboratory mix design for reuse fine-grained soils with high clay content involved in earthworks of a construction site should always consists of two main steps:

- the first one, focused on the classification and qualification of the soil involved in the earthworks [10]: geotechnical identification, localization, suitability for treatment, choice of the type of treatment (with sole lime or with lime and cement);
- the second one, focused on the mix design: determination of the binder content, in relation to the planned use, to the specific nature of the clay to be treated, to the actual characteristics of the binder to be used and, moreover, in relation to the predictable water content of the soil at the moment of executing the works.

Typically, in Italy the Specifications regarding the soils and the lime to be used are those given in Table 1; partially taken from related European Standards [7] [10] [11] [12] [13].

Table 1. Suitability criteria and requirements for the components of a soil-lime mixture

Component	Criterion	Threshold
Soil	• Gradation	if possible < 63 mm if possible $p_{0.063\ mm}$ > 12 %
	• Plasticity (PI)	if possible PI > 5 %
	• Content in organic substances	embankment:. < 4 % subgrade < 2 %
	• sulfates and sulfures(1)	embankment < 0.1 % subgrade < 0.25 %
	• Volumetric Swelling Gv	embankment: < 10 % subgrade < 5 %
Air lime: • quick lime (ground)	• Fineness (degree of pulverization) • content in free calcium oxide (% CaO) • Water reactivity test	Category 1; Category 2 CL 90-Q ; CL 80-Q ≥ 60°C within 25’
• hydrated lime (powder, milk of lime)		CL 90-S ; CL 80-S

NOTE (1): a total content of sulfur salts lower than 0.25% is typically acceptable for subgrade, while for a higher content (in any case lower than 1%), a specific study of the behavior of the mixtures is necessary [14]

Identification of the minimum lime content to be used for lime-soil mixture may be carried out in two ways:

- according to the Swiss Standard SNV 640503a [15], this content is the minimum needed for modifying the initial plasticity of the soil and beyond which the plasticity index PI of the mixture does not change in a significant way. This is an indication which is extremely useful in the field for estimating the consistency of lime-soil mixtures, due to its implications with respect to the circulation of the working vehicles and to the earthmoving operations;
- according to the Standard ASTM D6276 [16], the minimum dosage in lime is the one that ensure flocculation of the clay compounds, and it may set as the one that implies a minimum pH of 12.4 in the mixture (it is known as Eades and Grim test).

Major discrepancies in the lime stabilization design methods as used in different countries mainly deal with testing methodologies and quality criteria related to the optimization of the mixture. In what follows, therefore, reference will be made to two different design methods adopted in Italy (one by the National Agency for road -

ANAS, the other by the Italian Railway Network - RFI), and comparing them with those in use in other Countries (France, Belgium and US), which have a wider experience in terms of applications and in situ validation.

4. French and Belgian design method

This method, that is used in France [4] [17] and, descending from it, in Belgium [18], primarily makes a distinction between mixtures to be used for embankments and mixtures to be used as subgrade.

4.1. Use in embankments

When designing soil-lime mixtures to be used in embankment (excluding the higher layer that, in effect, acts as the capping layer of the pavement structure, but including the subformation), lime treatment of clayey soils aims to allows the maximum reuse of water sensitive soils, even when at high water content, by ensuring in the final mixture adequate properties such as workability and compactibility for their correct laying.

The parameter (quality criterion) considered as the most adequate for characterizing the mixtures from the mechanical point of view is the Immediate Bearing Index (IBI) as determined on specimens compacted in the CBR mould, according to the Proctor test with standard effort [19] and tested with immediate penetration (within 90 minutes from mixing) with a plunger of standard area, without any soaking in water [11] or overloading. This index allows to globally evaluate short term performances of the mixtures, such as the bearing capacity, the workability, compactibility and suitability to bearing the traffic during the construction phases. The laboratory mix design consists, in this case, in carrying out compaction and immediate bearing capacity testing, as one, and in determining the variation of both the dry density, γ_d, and the IBI, when varying the water and the lime content. The results of this study, finally, should provide:

- rules about the final dosage to be adopted, as a function of the nature of the soil, and, mainly, of its hydraulic state, for fulfilling the requirements as prescribed for the mixtures;
- contractual targets for the quality control of the mixtures (binder contents and minimum water content during the compaction phase) as well as of the layers in situ (compaction degree, mechanical properties).

4.2. Use in capping layers

In this case, the interest of the lime or lime-cement stabilization consists not only in reusing the fine-grained soils involved in the works, but also in improving the bearing capacity of the subgrade and, therefore, the structural efficiency of the pavement, much more than is allowed by using granular materials. The mix design of the mixtures designed for capping layers will address: (i) the choice of the most suitable product for the treatment (lime or lime and cement); (ii) the determination of the minimum dosage that allows one to achieve, within the time and during the season as defined in the time schedule for the construction, the mechanical performances as considered in the design phase (quality thresholds); (iii) the evaluation of the effect that the different variables have on the performances mentioned and, in particular, the effect of the binder content, of the water content and of the mixture's density.

Table 2 summarizes the minimum IBI for laying operations, as a function of the soil plasticity and for different intended use of the stabilized mixtures. In the case of mixtures for embankment layers less than 2 m from the formation level of the pavement, it is necessary to comply with the additional requirement: CBR_{SP} /IBI ≥ 1.0 (CBR_{SP} being the bearing capacity CBR measured on specimens compacted in accordance to the Proctor procedure with Standard effort [19], and tested after 4 days of soaking in water). Furthermore, in order to verify the long-term requirements (for ensuring the durability during the service life) of the mixture for capping layers, in addition to the fulfilment of the swelling requirements, as preliminarily verified via accelerated volumetric swelling Gv evaluated after 168 hours of soaking in water at 40°C in accordance with the EN 13286-49 [20], the mechanical strength of the mixtures has to be assess, based on one of the following:

- unconfined compressive strength UCS, determined in accordance with the standard ASTM D 5102 [21], on cylindrical specimens with a height-to-diameter ratio of about 2 (for binary mixture soil-lime);
- indirect tensile strength (mainly for ternary mixtures lime-cement-soil), at different curing time.

Table 2. Minimum values of the IBI required for using lime-treated soil in embankments

	Minimum IBI values		
Plasticity Index PI of the soil	Embankment layers at a distance greater than 2 m from the formation level	Embankment layers less than 2 m from the formation level (excluding the capping layer)	Capping layers
PI < 12	10	12	20
12 ≤ PI < 25	7	8.5	15
25 ≤ PI < 40	5	6	10

The compressive strength is used for verifying the water and frost resistances of the stabilized soil. For soils that are not too plastic – characterized by means of the Methylene Blue value, MB < 6 [22] – a satisfactory water resistance is guaranteed when it results:

$$I = \frac{UCS_{(28+32i)}}{UCS_{(60)}} \geq 0{,}8 \quad (1)$$

where:

I: water resistance Index;

$UCS_{(28+32i)}$: the compressive strength of cylindrical specimens that after 28 days of normal curing (in protected condition), have been soaked in water for 32 days (at 20 ± 2 °C)

$UCS_{(60)}$: is the compressive strength of cylindrical specimens kept for 60 days in normal curing conditions,

For highly plastic soils (MB > 6) it is sufficient I > 0.6. As far as the frost resistance is concerned, this can be considered as satisfactory if, at a curing time corresponding to the foreseeable frost occurrence in situ, it is UCS > 2.50 MPa. In non-frost areas, for lime stabilized soils, as for soils with medium-high plasticity (PI>20), it is required:

CBR (standard effort) > 20 (2)

and

CBR (standard effort) > IPI (3)

As far as the target density in situ, for treated soils in embankments, this is set equal to the 95% of the maximum dry density, MDD, Proctor test with standard effort, and, in the case of capping layer, this requirement is set equal to the 98.5% of MDD (96% when evaluated at the bottom of the layer). Whenever a soil-lime mixture is supposed to provide a contribution to the overall mechanical strength (as it is for the upper part of the embankments), a minimum water content in the mixture has to be guaranteed since this is necessary for developing the pozzolanic reaction. This is done by imposing that the final water content of the stabilized soil, starting from the minimum water content of the range of natural ones of the untreated soil, ends up being higher that 90% of the optimum moisture content (OMC) of the soil-lime mixture, as determined with the Proctor test with standard effort.

5. US typical requirements

The procedures outlined by the National Lime Association, NLA [23] in order to optimize the amount of lime required for long-term strength, durability and the other desired properties of the stabilized soil includes:

- evaluation of the soil suitability for lime stabilization (gradation, plasticity, presence of organic or harmful chemical substances);
- determination of the minimum amount of lime required, via the Eades and Grim test [16];
- evaluation of the lime-soil performance for long term durability, paying attention to cyclic freezing and thawing and periods of extended soaking. For doing this OMC and MMD of the lime-treated Soil has to be determined, using ASTM D698 [19] procedures (standard compaction effort). Then, UCS specimens are fabricated at OMC (± 1%) with the minimum lime content. After 7 days of curing in air at 40°C, in protected condition, specimens are subjected to a 24 hour capillary soaking soak prior to testing for UCS;
- only for expansive soils, change in expansion characteristics is determined after capillary soaking, via Gv measurements.

In US, among the others, the National Lime Association recommends to make use of the UCS mechanical requirements evaluated on soil-lime specimens after 7 days of soaking in water, as detailed in Table 3:

Table 3. Soil-lime mixture Unconfined Compressive Strength [20] recommendations for various anticipated service conditions, in kPa [23]

Anticipated use	Extended soaking for 8 days	After *N* cycles of freeze – thaw[1]		
		N = 3	N = 7	N = 10
Subbase:				
a) Rigid pavement/ floor slabs/ foundations	345	345	620	830
b) Flexible pavement (thickness > 25 cm)[2]	420	420	690	900
c) Flexible pavement (thickness = 20 - 25 cm)[2]	480	480	690	965
d) Flexible pavement (thickness = 12 - 20 cm)[2]	620	620	900	1100
e) Base	900	900	1170	1380
Note				

NOTE:
1. Number of freeze-thaw cycles expected in soil-lime layer during the first winter of exposure
2. Total pavement thickness overlying the subbase

6. Italian design methodologies

6.1. RFI method

In Italy, the National Agency for Railways (RFI) applies an internal Technical Specification [24], that is based on a complex design methodology structured as follows:

- soil identification, basically as described in Table 1, but including a X-ray diffractographic examination;
- laboratory study of the soil-lime mixtures. The mechanical test here considered is the CBR with modified effort [25], and mixtures are tested after 7 or 28 days of curing in air, followed by 4 days of soaking. The IBI is also considered for determining the minimum lime dosage that ensures IBI = 10, independent on the plasticity of the soil. Furthermore, a standard Proctor compaction study is also required, together with the UCS (after 24hours, 7 days and 28 days of curing in air). As far as UCS testing is concerned, it should be noticed that the RFI Specification does not set any specific requirement in relation to the intended use of the mixture. Furthermore, both linear and volumetric swelling have to be determined, for the mixture with IBI > 10: an admissible limit of the 1% is given, without specifying the testing standards to comply with;
- full-scale in situ testing on a trial embankment, in order to validate the laboratory results for the optimum lime dosage and the laying conditions. At least two optimized mixtures have to be laid with different compaction effort (number of roll passes). This is a peculiar aspect of this Specification [26], which is largely inspired to the French method but defines the final mixture via in situ testing for determining the deformation modulus Md with loading plate [27], on at least 5 different locations of each layer of the trial embankment, at different curing time (0, 1, 3 and 7 days after compaction). On the upper layer, the deformation modulus after 30 days has to be determined, together with in situ CBR, density controls and moisture content determination on areas close to the modulus testing.

It is clear that this procedure is really money and time consuming, since at least 6 weeks are necessary for the third phase alone, together with the availability of laboratory and field equipment. This kind of method may be justified only for major works, such as the railways, where large volume of homogeneous soil have to be treated. In the case of minor construction sites, this method is not applicable.

6.2. ANAS method

On the other hand, in Italy, the National Agency for Roads (ANAS), makes use of an internal specification for soil-lime mixtures [28], based on a laboratory study that includes Proctor compaction studies, CBR bearing capacity and UCS tests.

Nevertheless, this specification prescribes the modified effort for the compaction test (which corresponds to an energy level much higher – 2.69 MJ/m^3 - of that gained with the standard effort – 0.6 MJ/m^3). Again, the CBR is determined on mixtures cured for 7 days in air, with protected conditions, and 4 final days of soaking in water at 20°C (7+4s). The linear swelling (LS) too is measured on specimens cured with such curing procedure. Table 4 summarizes the ANAS requirements for soil-lime mixture:

Table 4. ANAS requirements for soil-lime mixture [28]

	CBR(7+4s) (%)	linear swelling LS (%)	Md (MPa)
Embankment layers at a distance greater than 2 m from the formation level	> 30	< 1.5	> 20
Embankment layers less than 2 m from the formation level (excluding the capping layer)	> 60	< 1.0	> 50
Capping layers	> 60	< 1.0	> 50

7. Conclusions

For comparison of the design methodologies for lime-soil mixtures described in this paper, special attention should be paid to the design criteria proposed for evaluating the mechanical performances of this kind of mixtures as well as their compaction in the field. It has been highlighted that some Italian specifications make use of criteria that prescribe a high energy level (modified Proctor effort) when producing the specimens for compaction and CBR testing, instead of the normal effort (as considered by other international design methods). As a consequence, the reference to the modified effort for compaction of the mixture may lead to various problems. First of all, it should be remembered that the performances of a mixture improve with its density and, therefore, if the design phase is based on high levels of dry densities that are not likely to be achieved in the field, there is a serious risk of overestimating the mechanical performances of the mixtures. Secondly, for the specific case of lime stabilization, it is necessary to pay attention to the moisture content of the mixture during compaction, since this is crucial not only for correctly compacting the material on site, as for soils, in general, but also (and above all) for achieving the required mechanical performances in the medium-long term, as allowed by the development of a pozzolanic reaction within the mixture.

In fact, it should be observed that for natural soils the optimum moisture content, OMC, defined with the modified Proctor test, still falls within the range of the moisture content that ensures good mechanical performances in the field, although being very close to the upper limit. In the case of the lime stabilized soils, this OMC may fall below the minimum water content required for allowing flocculation of the clayey fraction of the soil, hydration of the chemical compounds deriving from dissolution of clay minerals, and the development of the pozzolanic reaction. This minimum water content, as an example, is that prescribed by the French design method defined in SETRA [4] [17].

Vice versa, during the design phase, if the references for the mixture compaction are set with respect to realistic energy levels, such as those considered in the standard Proctor test, this allows one to foresee, with high reliability, the real performances of soils, once they are in place.

Based on the previous considerations, an experimental plan for evaluating the level of agreement (or disagreement) of the different design methods and specifications has been defined, based on compaction studies of mixtures at different energy levels, with different lime contents, and for different curing times (in air and soaking), as detailed in Part 2.

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